PTTI-Aided Ephemeris Calculation and Rapid Data Link Acquisition for Manned Space Flight

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Abstract

Complexity of future manned space flight mission control can be significantly reduced by integrating GPS, the PTTI source, into telemetry, tracking and command (TT&C). Future telecommunications, space tracking electronic intelligence, metrology, navigation, and data acquisition will thereby be served, including: 1) On-board ephemeris determination, 2) Reduced synchronization time for time division multiple access (TDMA) links, and 3) In-flight clock calibration, increasing on-board autonomy and reducing ground support costs.

Manned space transportation through the first quarter of the 21st century will probably depend on a mix of vehicles, including the Advanced Manned Launch System (AMLS), the Personnel Launch System (PLS), and continued use of the Shuttle Fleet. Precise Ephemeris is important on-board for mission success, status monitoring, also for rendezvous and docking. Use of GPS can eliminate ground based tracking/processing, enhancing autonomy and reducing communications bandwidth.

GPS time can simplify complicated functions used in bandwidth efficient time division multiple access (TDMA) communications, such as: 1) Precise and real-time synchronization of receive reference timing, 2) Transmit-timing and acquisition control, 3) Unique synchronization word (UW) detection, and 4) Elastic buffering. High clock accuracy provides increased signal-to-noise (S/N) ratio during acquisition, permitting narrower acquisition frequency and time windows.

Spaceborne systems requirements to provide capabilities such as: 1) Refinement of the GEM-72 gravity model based on satellite tracking observations from ATS-6 to GEOS-3, 2) Relativistic clock experiments, 3) NASA crustal dynamics program for developing space geodetic techniques to study the earth's crust, its gravity field, and earthquake mechanisms, and 4) Multi-disciplinary space geodetic tracking for studying global climatic changes are also reviewed.

A. INTRODUCTION

Future space vehicles will require a very precise time reference for communication and navigation functions, including: 1) Timing signals to maintain user synchronization within various digital spread spectrum communications networks, 2) Accurate clocking to encryption devices for military missions, to maintain security, and 3) Generation of a *"real time"*, time base to support integrated navigation functions, network acquisition, sensor data processing, correlation and fusion. Some speculation concerning potential additional PTTI-aided space applications is included at the end of this paper.

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Independent redundancy, to assure reliability, also implies synchronization among the independent data sources, either 1) Loosely, involving buffering, comparing or voting, signaling consensus and/or marking completed intervals, or 2) Tightly, involving hardware comparison of voting, and a common time reference, whereas loose synchronization can employ separate time references.

B. SPACE SHUTTLE ORBITER (SSO) TIMING & CONTROL PROCESSING

1) MASTER TIMING UNIT

The Space Shuttle stable crystal-controlled master timing unit provides serial time reference signals to the on-board computers, pulse code modulation master units (PCMMUs), various time display panels, and synchronization to instrumentation and other subsystems, using separate GMT and Mission Elapsed Time (MET) time accumulators, as shown in Figure 1. Time outputs are a) Serial time code continually updated at 100 pps rate (IRIG-B), and b) Self-clocking Manchester II bi-phase demand outputs read out upon receipt of externally supplied enable signals.

Frequency stability is better than 1 part in 10^9 per day long term, and 1 part in 10^{10} standard deviation short term, using the Allan variance formula for averaging times of 0.5 1, 2, and 10 seconds, but requires 72 hour stabilization time after a power-off state at 35 deg.F. Master Timer derived time/clock/sync inputs to Shuttle operational instrumentation (OI) are shown in Fig. 2.

2) AVIONICS PERFORMANCE

The estimated three-sigma position and velocity errors at main engine cutoff (MECO) of about 4600 ft and 20 ft/sec could be updated in the post-MECO state to about 100 ft and 0.6 ft/sec in about 2 minutes, using GPS.

On-orbit TDRSS provides adequate state vectors using two-way range rate (Doppler) data through both satellites within one revolution, in about 60-90 minutes. With only one relay satellite available, the 1.5 pass minimum tracking interval is about 115 minutes. An integrated time line suggests that 120-195 minutes. are required from the start of tracking to maneuver execution. With a full GPS constellation the state could be determined within about 2 minutes, as for the post-MECO state. Updating and resetting externally requires use of the data processing system.

For ground entry navigation, using C-Band radar, the mission control center (MCC) updates on-board knowledge of position after blackout at about 150 kilofeet. altitude. GPS could provide accurate post-blackout navigation capability to about 200 ft and 1.2 ft/sec, or much better in differential mode. An orbiter GPS Development Flight Test (DFT) demonstration is planned for 1993 (Figure 3).

C. FUTURE MANNED SPACE VEHICLES AND THEIR AVIONICS ARCHITECTURES

Autonomy levels in future space avionics architectures will undoubtedly be increased, most likely with on-board health status processors as a first step, as shown in Figure 4, and on-board PTTI-

aided ephemeris determination and communication link synchronization not far behind.

Future manned space transportation will probably depend on a mix of vehicles, as indicated in Figure 5. On-going NASA studies have resulted in preliminary designs of Advanced Manned Launch Vehicle (AMLS) and Personnel Launch System (PSL), while anticipating continued use of the Shuttle Fleet through the first quarter of the 21st century [13]. A comparison of vehicle sizes is shown in Figure 6.

D. PRECISE TIME, FREQUENCY AND EPHEMERIS DETERMINATION

Of the various available systems, only Loran and GPS are capable of time synchronization to better than 100 nanoseconds, as shown in Figure 7, while differential GPS is capable of another order of magnitude improvement [12].

1) ON-BOARD TIME AND FREQUENCY

One nanosecond (ns) of time error is equivalent to 0.3 m range error. A spaceborne GPS system can provide precise time globally to an accuracy of 103 ns, as shown in the total RSS time transfer error budget of Table 1 [4, 6, & 11]. Accuracies to better than 10 ns, can be obtained by correcting for ionospheric delays with simultaneous view for coordinated users.

The Russian GLONASS, capable of similar accuracies relative to GLONASS UTC, has a known relationship to UTC (USNO) via the International UTC maintained by the Bureau International des Poids et Mesures (BIPM), Sevres, France, and could supplement GPS data to achieve reliability/availability levels demanded by the FAA and ICAO for commercial aviation.

GPS time is determined by the USNO Master Clock (MC) of the USNO Time Service Department (TS). GPS can provide UTC (USNO) time after correcting for the difference from UTC by an integral number of seconds. GPS system time is on a continuous time scale, referenced to midnight 5 Jan 1980, whereas UTC and Russian GLONASS time contain leap seconds that allow for the deceleration of the earth rotation. This number is provided as part of the navigation message, because it changes every time there is a leap second.

Upon network synchronization, the clock, timing signals, and real time base, derived from accurate crystal or rubidium frequency standards of performance summarized in Figure 8 and Table 2, will be slaved by software controlled by an assigned network controller, referenced using GPS, UTC or GMT [12].

Treating GPS as a Precise Time and Time Interval (PTTI) distribution system, semiconductor laser optical clock distribution can provide a virtually jitter-less timing source, if required. Accumulated dynamic clock jitter between ports of both correlated and uncorrelated sources is of the order of picoseconds [7].

2) PRECISE EPHEMERIS DETERMINATION

Precise ephemeris data is important on-board for mission success, status monitoring, also for rendezvous and docking. TDRS measures to better to better than 100m accuracy, but does not give instantaneous position fixes, as does GPS. Presently 60 to 195 minutes elapses between the start of tracking and the start of executing maneuvers. In low earth orbit, unpredictable atmospheric drag is the largest limit on prediction.

E. COMMUNICATIONS AND DATA SOURCE SYNCHRONIZATION

Using a GPS timing reference, communications with other GPS users can inter-operate immediately without first exchanging timing signals. Sub-microsecond accuracy timing derived from GPS brings new meaning to *"real time"*, in computer and communications synchronization.

1) END-TO-END LINK SYNCHRONIZATION

Carrier, clock, code, and network synchronization needs are summarized in Figure 9. A TDRS functional receiver block diagram, and a representative end-to-end communications block diagram, are provided in Figures 10 and 11 respectively [1, 2, & 14].

TDRSS provides short code PN lock acquisition with > 90% probability within 20 seconds at S/No values between 34 and 73 dB-Hz, and within 7 seconds for S/No >37 dB-Hz, and carrier within 10 seconds. TDRSS user transponders provide Doppler compensation within 1500 Hz of actual transponder center frequency, allowing for about 1% velocity uncertainty. GPS-derived velocity error is closer to 0.01%. Code acquisition strategies are matched to TDRSS-derived predicted position uncertainties.

With reduced GPS position and velocity uncertainties, acquisition windows could be considerably reduced in both time and frequency, leading to reduced sync times at increased S/No ratios. GPS time can also simplify the most complicated functions used in bandwidth efficient Time Division Multiple Access (TDMA) communications: precise and real-time synchronization of receive reference timing, transmit-timing control, acquisition control, unique synchronization word (UV) detection, and elastic buffering [7].

2) DATA SOURCE SYNCHRONIZATION

Independent redundancy requires some form of synchronization among the independent data sources. Soft, or loose, synchronization involves buffering, signaling consensus, and marking completed intervals, under program control over suitable inter module data links. Hard, or tight, synchronization requires hardware comparison or voting, and a common time reference. As used in the NASA Fault Tolerant Multi-processor (FTMP) and other high reliability concepts for manned aerospace vehicles, the timing reference must continuously remain within tolerances for time-correlated data transfer.

In the past, continuous timing references were maintained using fault-tolerant redundant clock distribution, based on majority logic voting algorithms. A set of GPS disciplined voltage-controlled

phase-locked crystal oscillators can ensure that failure of one of the oscillators does not destroy the phase lock of the survivors. Normally all clock receiver outputs are in phase lock with each other and with all the oscillators [12].

F. IN-FLIGHT CLOCK CALIBRATION FOR REDUCED REACQUISITION "TIME TO FIRST FIX"

Many aerospace vehicles carrying atomic clocks to provide precise time to their communications systems need to be calibrated before take-off. With a GPS receiver on-board they can be reset or calibrated in flight. The clock can then be used to reduce time to first fix (TTFF) if the receiver has to reacquire satellites, and enables it to perform direct P-Code acquisition.

G. ENVIRONMENTAL STUDY REQUIREMENTS

Although widespread need for highest PTTI accuracy may not be apparent, numerous applications for this accuracy will surface once the availability has been established. For instance, it may be of interest to review PTTI requirements of a PLS-type vehicle for supporting various environmental study programs.

1) GRAVITY MODEL REFINEMENT

Precise GPS techniques are making possible new kinds of large scale surveys of the earth and its resources using aerospace platforms. The use of GPS receivers in space vehicles for decimeter-level space navigation and geophysics - including gravity field determination - will map broad global features of the gravity field, while future aircraft equipped with GPS will chart fine, regional details of the same field.

Gravity Probe B (GP-B) used GPS as a sensor for a closed loop space guidance system, from its location after initial insertion to a very precise low earth orbit, to within 0.001 eccentricity, to within 0.001 degree inclination, and to alignment with the star Rigel to within 0.001 degree [3].

2) RELATIVISTIC CLOCK EXPERIMENTS

Gravity Probe-B was also part of a NASA project that tested two aspects of Einstein's relativity theory, to verify two gyroscope spin axis motions in earth orbit not predicted by Newtonian analysis. In a precisely polar orbit the two effects would be orthogonal, with magnitudes calculated to be 6600 and 42 milliarc-sec/year respectively [3]. The required long term clock stability is about 10^{-13}, or an accuracy of 10 ns, to successfully accomplish the relativistic clock experiment [5].

3) NASA CRUSTAL DYNAMICS PROGRAM FOR EARTHQUAKE MECHANISMS STUDY

Movements of the earth's crust include extremely slow centimeters per year movements of the continents relative to one another, and also their slow internal deformations. Measuring distances

between points up to thousands kilometers apart with accuracies exceeding a few parts in 100 million enables such movements to be detected.

Precision and accuracy of ground based GPS determined inter-station vectors for 50 - 450 km baselines were recently reported as better than 30 mm horizontally and 80 mm vertically, by comparing with very long baseline interferometry measurements. Such measurements provide details about strain across faults of plate boundaries [8].

4) SPACE GEODETIC TRACKING FOR GLOBAL CLIMATIC CHANGE STUDIES

The TOPEX/Poseidon oceanographic satellite will measure the topography of the open oceans using radar altimeters to a precision of a few cm. Measuring open ocean circulation and sea level as an indicator of global warning depends on detecting global sea level changes of about 1 mm/year [9].

Tide gauges presently used measure relative change between the land surface and sea levels. This relative change may be due to sea level rise or land subsidence or both. Satellite altimetry measurements will have to be related to a well defined terrestrial and space reference frame that must remain valid for decades, with respect to a network of earth fiducial points [9].

H. ENVIRONMENTAL STUDY SUPPORT

Reviewing the PTTI capabilities of a GPS-equipped PLS-type vehicle, potentially to support *"Mission to Planet Earth"*, environmental studies, the following presently appear unlikely: 1) Precision orbit injection to support GP-B-type gravity model refinement, or PTTI precision to support 2) GP-B-type relativistic clock experiments, 3) Monitoring earth crust movements,s or 4) Monitoring sea level changes for tracking climatic changes.

However years after dedicated environmental satellites have completed their missions, clearly a PLS-type vehicle will be able to measure long-term drifts, and to monitor relative movements of earth fiducial points.

I. SUMMARY AND CONCLUSIONS

GPS on-board time, synchronized to the GPS space segment, provides the extremely precise reference needed for navigation, positioning purposes, can serve as primary time transfer system, as well as for telecommunications, space tracking electronic intelligence, metrology, and data acquisition.

Discretionary use of the PLS vehicle, with GPS on board, as a flexible platform to perform environmental studies will depend on the PTTI availability, and - at the very lease could identify long-term relative movements of earth fiducial points established for various local or global reference frames.

Continuous on-board filtering and orbital element updating based on GPS can eliminate ground-based state vector updates, provide earlier payload deployment opportunities, save fuel due to reduced dispersion rendezvous, make up for loss of TACAN by the year 2000, also reducing communications bandwidth [10].

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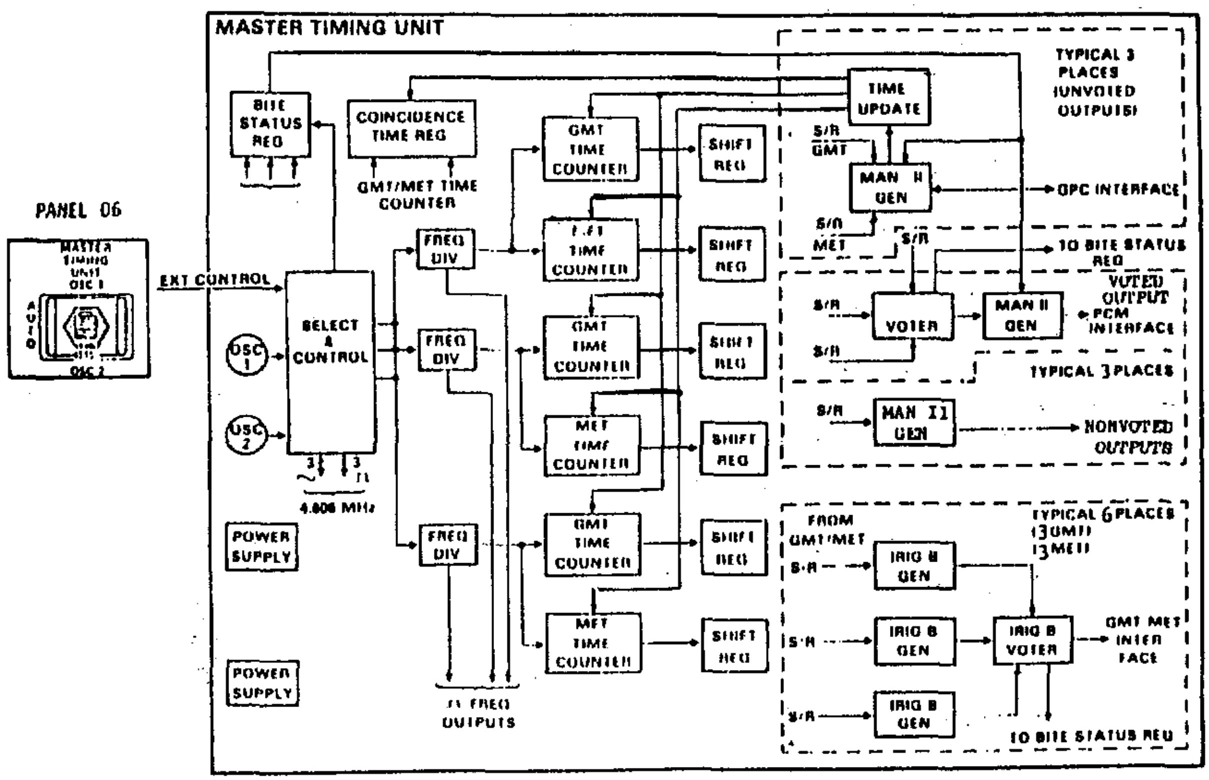

Figure 1. Space Shuttle Orbiter (SSO) Master Timing Unit (MTU)

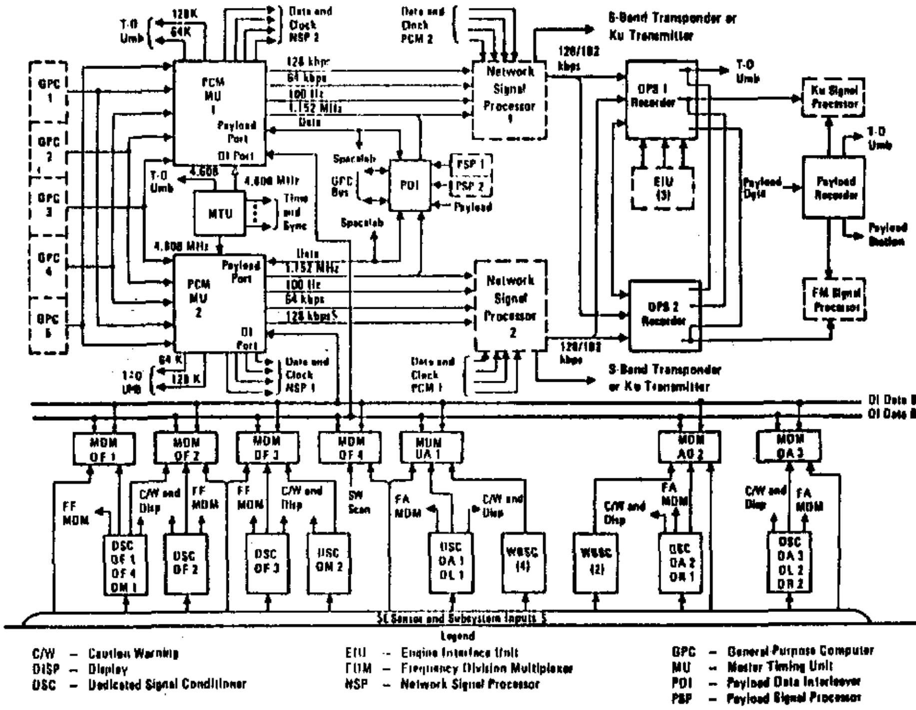

Figure 2. Time/Clock/Sync Inputs to Operational Instrumentation (OI)

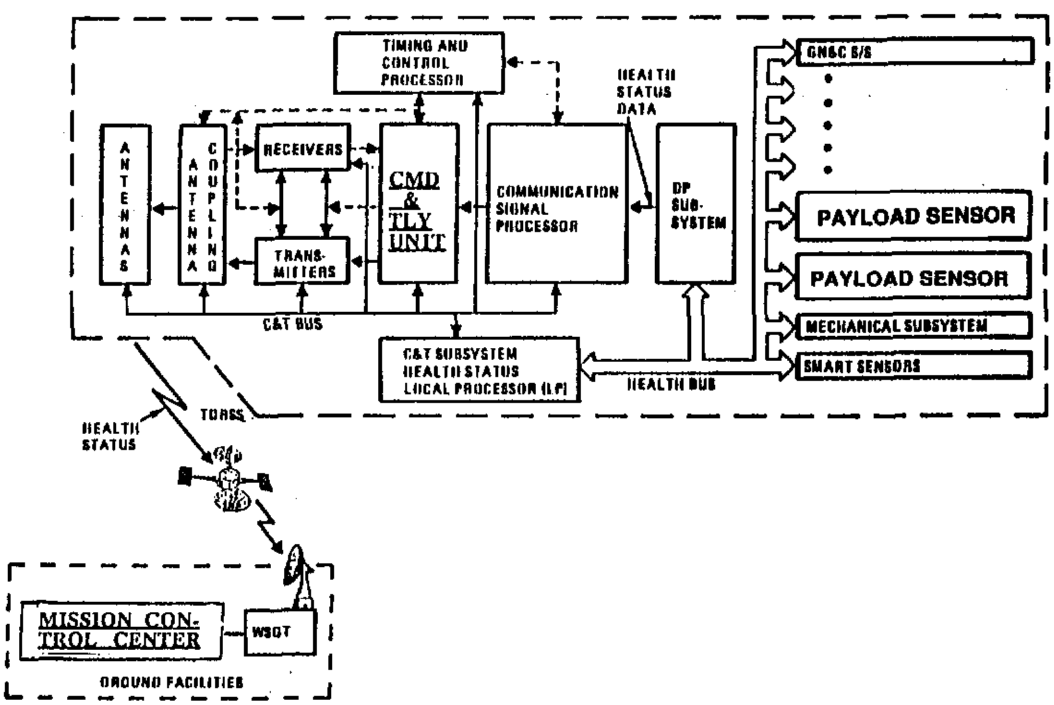

Figure 3. Timing and Control Processor Interface to Command & Telemetry Unit (Partial Autonomy: Onboard Health Status Processor)

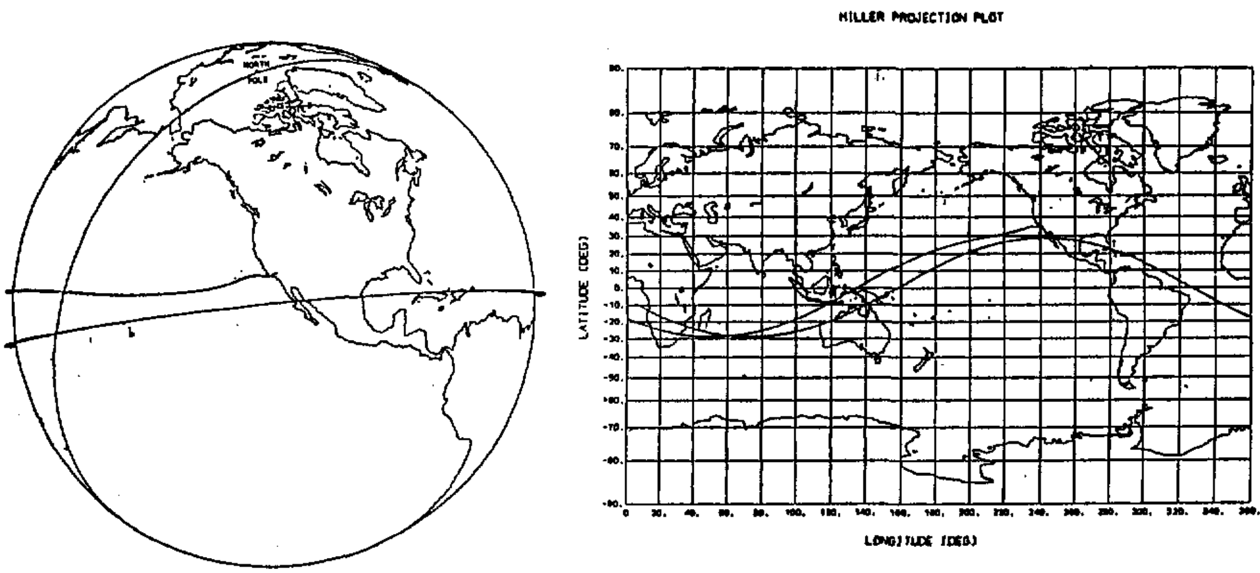

Figure 4. Space Shuttle GPS Developmental Flight Test (DFT) Profile: Orbit, Deorbit, and Entry

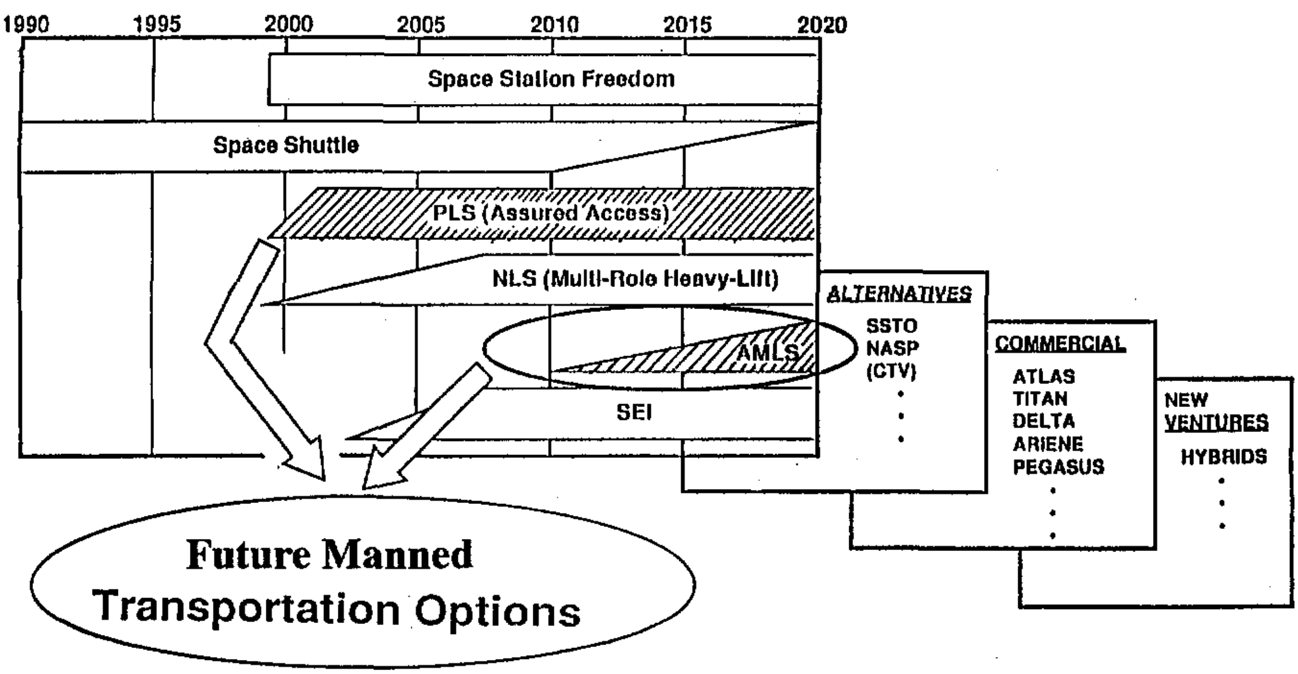

Figure 5. Role of AMLS & PLS in the Future Manned Space Transportation System

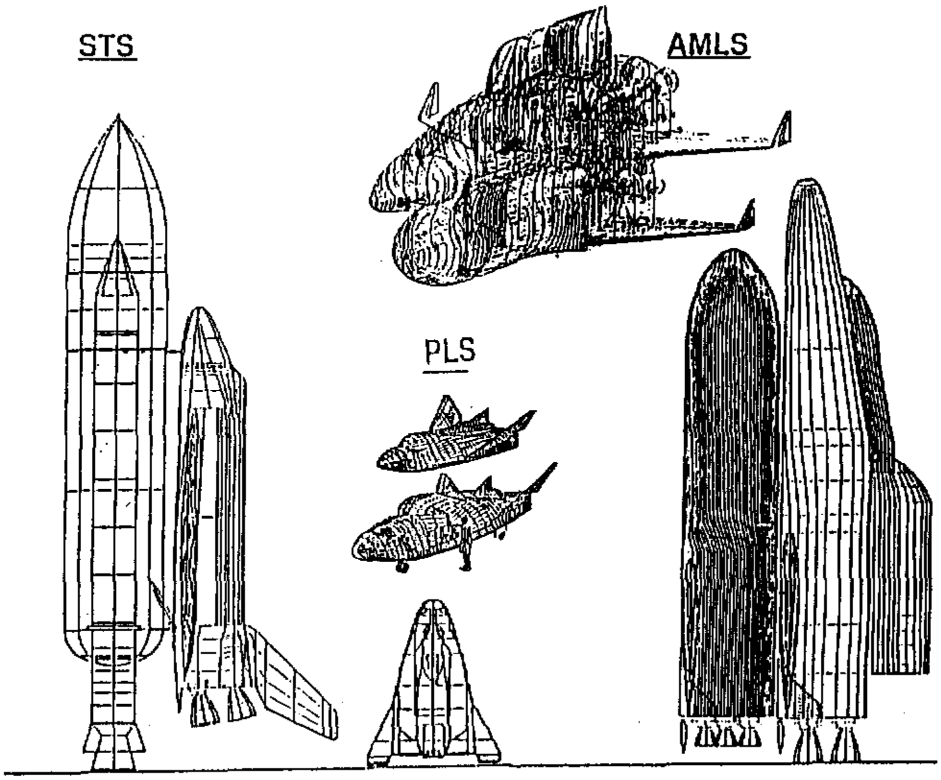

Figure 6. Relative Sizes of STS, AMLS, and PLS

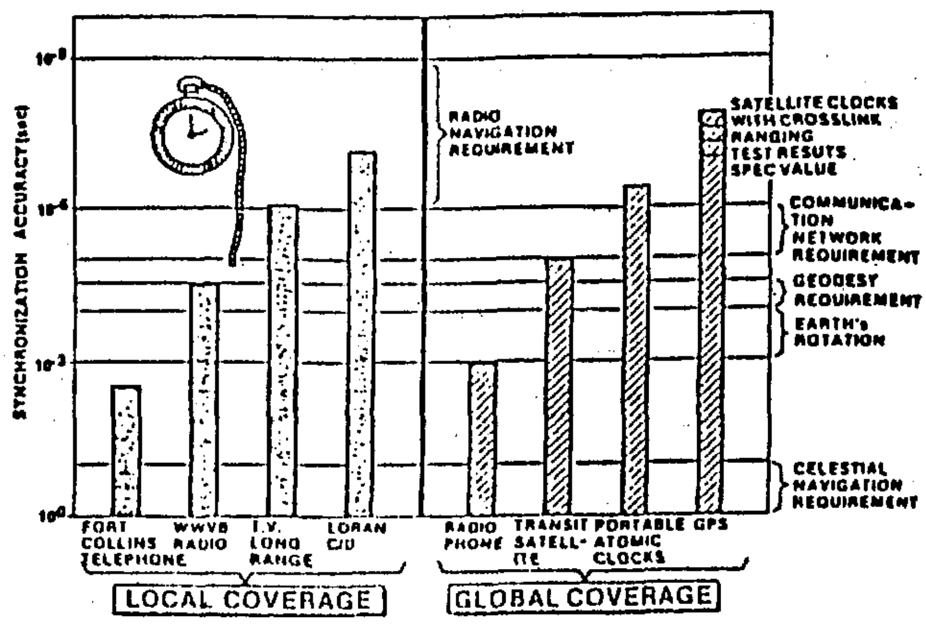

Figure 7. Time Synchronization Capabilities of Various Systems

	ERROR SOURCE	C/A-CODE RAW MEASUREMENTS (ns)	C/A-CODE SMOOTHED MEASUREMENTS (ns)	P-CODE RAW MEASUREMENTS (ns)	P-CODE SMOOTHED MEASUREMENTS (ns)
SPACE	CLOCK AND NAV SUB-SYSTEM STABILITY	0	0	0	0
SPACE	PREDICTABILITY OF SATELLITE PERTUBATIONS	0	0	0	0
SPACE	OTHER	0	0	0	0
CONTROL	EPHEMERIS PREDICTION MODEL IMPLEMENTATION	0	0	0	0
CONTROL	OTHER	0	0	0	0
USER	IONOSPHERIC DELAY	0-30	0-30	0-7	0-7
USER	TROPOSPHERIC DELAY	0-6	0-6	0-6	0-6
USER	RCVR NOISE	32	5	6	1
USER	MULTIPATH	5	5	5	5
USER	OTHER	2	2	2	2
USER	POSITION ERROR	71	71	34	34
TOTAL ERROR	POSITION UNKNOWN	78.1-83.8	77.6-63.5	34.5-36.1	34.4-35.6
TOTAL ERROR	POSITION KNOWN	32.4-44.6	7.3-31.5	8.1-12.2	5.5-10.7

COMPONENT	ERROR [ns] (1σ)
US NAVAL OBSERVATORY	
MEASUREMENT COMPONENT	70
CONTROL SEGMENT COMPONENT	30
GPS TIME PREDICTABILITY	47
NAVIGATION MESSAGE QUANTIZATION	3
SATELLITE ORBIT	11
SATELLITE CLOCK	32
SATELLITE GROUP DELAY	6
DOWNLINK AND USER EQUIPMENT	33
TOTAL (RSS) TIME TRANSFER ERROR BUDGET	103

Table 1b. GPS System Error Budget
(Factor of 6, the Estimated Reduction of Receiver Noise Factor due to Smoothed Measurements was used)

Table 1. Coordinated Time Transfer Using GPS

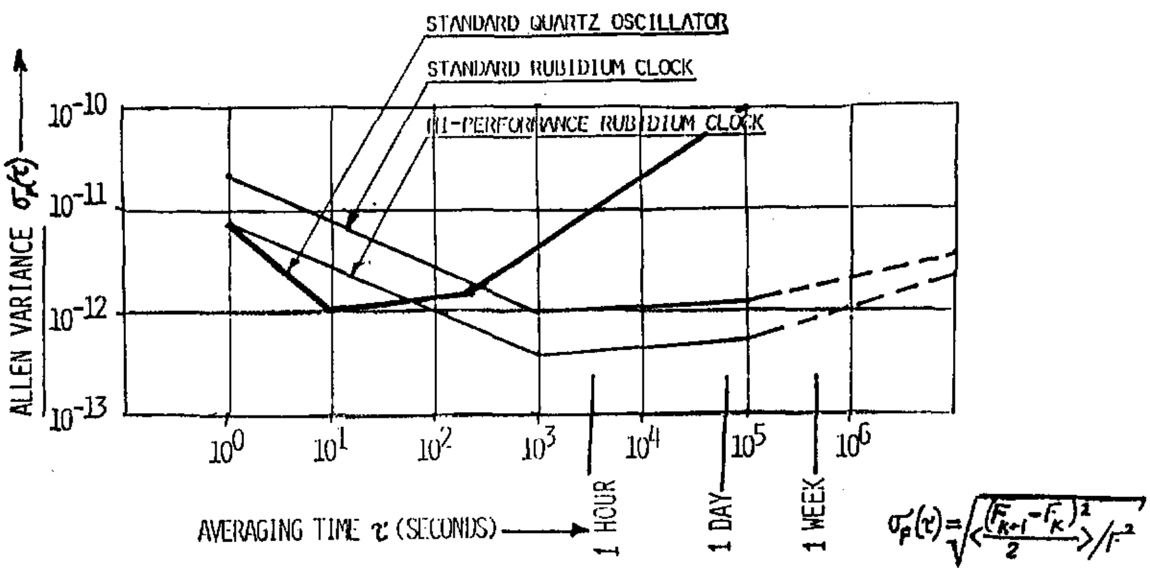

Figure 8. Comparison of Quartz Crystal Oscillator & Rubidium Clock Frequency Stability

DEFINTION: SYNCHRONIZATION IS THE PROCESS OF ALIGNING THE TIME SCALES BETWEEN TWO OR MORE PERIODIC PROCESSES THAT ARE OCCURRING AT SPATIALLY SEPARATED POINTS

1 CARRIER SYNC - REQUIRED FOR OPERATION OF PHASE-COHERENT DEMODULATOR. THE LOCAL CARRIER REFERENCE MUST AGREE CLOSELY IN FREQUENCY & PHASE WITH THE RECEIVED SIGNAL

2 CLOCK SYNC - EFFICIENT DATA DETECTION REQUIRES THAT THE RECEIVER KNOWS WHEN ONE DATA SYMBOL ENDS AND THE NEXT ONE BEGINS. A LOCAL CLOCK IS REQUIRED THAT IS ACCURATELY TIME-ALIGNED WITH RECEIVED PULSES

3 CODE SYNC - THE DECODER CANNOT OPERATE UNLESS THE RECOVERED SYMBOLS CAN BE SEPARATED INTO THE PROPER GROUPS. WITH CONVOLUTIONAL CODES, DECODER MUST ACHIEVE AND MAINTAIN NODE SYNC.

WITH BLOCK CODES, DECODER MUST ACHIEVE AND MAINTAIN WORD SYNC. WITH TIME DIVISION MUTIPLEX, THE DATA REGENERATOR MUST BE IN SYNC WITH DATA SAMPLES (FRAME SYNC).

4 NETWORK SYNC - REQUIRED IF DIGITAL DATA ARE RECEIVED FROM SEVERAL SOURCES, PROCESSED, AND RETRANSMITTED TO ONE OR MORE USERS THRU SWITCHES.

Figure 9. Types of Synchronization

SYSTEM PARAMETER	QUARTZ CRYSTAL OSCILLATOR	RUBIDIUM CLOCK
PRIMARY/SECONDARY STANDARD	NO	SECONDARY 6.834,682,613GHZ
FUNDAMENTAL WEAROUT MECHANISM	BASICALLY NONE	BASICALLY NONE
MAINTENANCE	BASICALLY NONE	BASICALLY NONE
PORTABILITY	VERY PORTABLE	VERY PORTABLE
APPLICATION	SPACE-AIR-GROUND	SPACE-AIR-GROUND
APPROXIMATE SIZE WEIGHT POWER COST	3" x 3" x 3" 1-2 LBS 2-5 WATTS $1.5K-4K	3" x 3" x 4.5" 2-4 LBS 10-18 WATTS $4K-8K
SHORT TERM STABILITY TAU (τ) = 1 SECOND	$\sim 1 \times 10^{-11}/10^{-12}$	$\sim 1 \times 10^{-11}$
STABILITY (ALLEN VAR) $\sigma_F(\tau)$ AT 1 DAY	$\sim 1 \times 10^{-10}$	$\sim 1 \times 10^{-12}/10^{-13}$
DRIFT/DAY	$\sim 1 \times 10^{10}$	$\sim 1 \times 10^{-12}/10^{-13}$
DRIFT/YEAR	$\sim 1 \times 10^{-7}$	PARTS IN 10^{10}
RETRACE	$\sim 1 \times 10^{-9}$	$\sim 1 \times 10^{-11}$
WARM-UP TIME TO PARTS IN 10^{10}	HOURS	$<$ 2 MIN TO PARTS IN 10^{10}

Table 2. Comparison of Quartz Crystal Oscillator & Rubidium Clock System Parameters

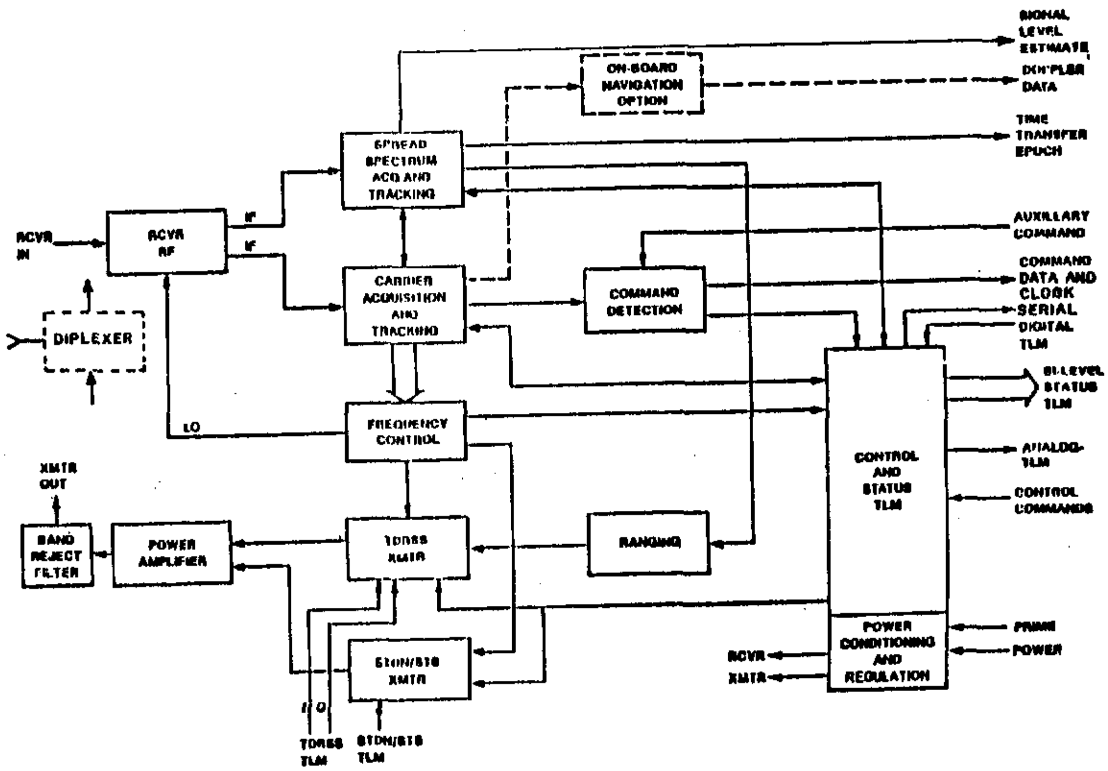

Figure 10. TDRSS User Transponder Functional Block Diagram

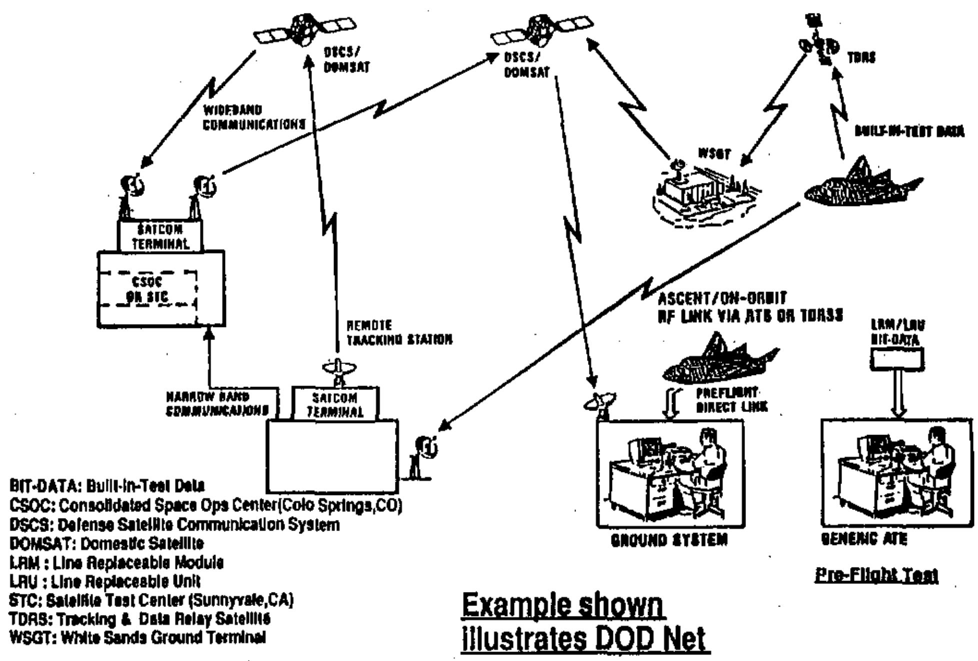

Figure 11. Universal GPS Time Reference Usage Will Aid Communications Synchronization

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QUESTIONS AND ANSWERS

R. Keating, USNO: It seems to me that tight integration of such complex systems can produce some rather adverse effects. For example, in the GPS system, if you have tight control you can mask relativistic effects. It seems to me with your system you are also creating a very grave danger of masking poorly understood physical effects - such as relativistic effects.

A. Anderman, Rockwell Space Systems Division: Basically I was trying to see to what extent such a platform could be used for various kinds of measurements. I mentioned for those type of measurements you probably could not ever have the right stability and constancy and so on. Plus the fact that even having personnel on board would provide certain amount of vibration and other noise effects. There are some areas which I did not get into on mapping other quantities where some very useful measurements might be performed.